

# Effects of electron correlation on the photocurrent in quantum dot infrared photodetectors\*

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## Abstract

The effect of electron correlation on the photocurrent of self-assembled InAs/InGaAs quantum dot infrared photo-detector (QDIPs) is studied. It is found that Coulomb interaction and level mixing in the many-body open system lead to double peaks associated with the intra-band transitions involving two lowest levels of the quantum dot. Furthermore, the photocurrent is a nonlinear function of the steady-state carrier density and it displays a plateau due to Coulomb blockade.

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Recently, many efforts have been devoted to the understanding of transport properties in quantum dot photo-detectors (QDIPs)[1,2]. The advantage of the QDIP over quantum well photo-detectors (QWIPs) is that light can be directly coupled to the electrons in the normal incidence geometry due to the effect of QD confinement in directions perpendicular to the growth axis and the dark current is smaller for the same detection wave length considered[3]. Other significant features that are unique to QDs include the Coulomb blockade effect[2] and phonon bottleneck[4].

Due to the localized nature of electrons in QDs, it is essential to take into account the effects of Coulomb blockade in the analysis of photoresponse of QDIPs, which in general can be ignored in QWIPs. For the non-equilibrium system considered here, it is convenient to use the Keldysh Green function to calculate the transport and optical properties while including the electron correlation. This technique has been used extensively in the study of nonlinear transport properties of quantum systems[5,6].

We solve the Anderson Hamiltonian of a two level system coupled with leads in the presence of an electromagnetic radiation with frequency  $\omega$ . We adopt the approach given by Jouho et al[5,6] and extend it to the present case with asymmetric tunneling rates. We find that the time averaged tunneling current is given by

$$\langle J(t)_j \rangle = (\Gamma_j^R - \Gamma_j^L) \frac{e \langle N_j(t) \rangle}{2} - e \int \frac{d\epsilon}{\pi} [\Gamma_j^L f_L - \Gamma_j^R f_R] \text{Im} G_j^r(\epsilon, \omega) \quad (1)$$

where  $\langle N_j(t) \rangle$  is the electron occupation number at QD,  $f_L = f(\epsilon - \mu_L)$  and  $f_R = f(\epsilon - \mu_R)$  are the Fermi distribution function of the left lead and right lead, respectively. The chemical potential difference between these two leads is related to the applied bias ( $V_a$ ) via  $\mu_L - \mu_R = eV_a$ .  $\Gamma_j^L$  and  $\Gamma_j^R$  denote the tunneling rates from the QD to the left and right leads, respectively, for electrons in level  $j$ .  $G_j^r(\epsilon, \omega)$  is the retarded Green function for an electron in level  $j$  of the QD. The first term in Eq. (1) for the excited state ( $j = 2$ ) provides the photo-induced tunneling current which exists only when  $\Gamma_2^R \neq \Gamma_2^L$ , a condition that can occur in a system with asymmetric potential.

Since the incident radiation considered in QDIP application is usually very weak, we can

ignore the renormalization of the retarded Green's function due to electron-photon interaction. Thus, we have (within the Hartree-Fock approximation)

$$G_1^r(\epsilon) = \frac{1 - N_1}{\epsilon - E_1 + i\Gamma_1/2} + \frac{N_1}{\epsilon - E_1 - U_{11} + i\Gamma_1/2},$$

$$G_2^r(\epsilon) = \frac{1 - N_1}{\epsilon - E_2 + i\Gamma_2/2} + \frac{N_1}{\epsilon - E_2 - U_{12} + i\Gamma_2/2},$$

where  $U_{11}$  denotes the Coulomb interaction between two electrons in level 1 and  $U_{12}$  denotes that for one electron in level 1 and the other in level 2. To calculate the steady-state electron occupation number for the QD, we solve the semiconductor Bloch equations for the two-level system coupled to leads and the electromagnetic radiation.[6] We obtain (for  $N_2 \ll N_1$ )

$$\Gamma_1 N_1 = -Im\mathcal{X} - \int \frac{d\epsilon}{\pi} [\Gamma_1^L f_L(\epsilon) + \Gamma_1^R f_R(\epsilon)] ImG_1^r(\epsilon),$$

$$\Gamma_2 N_2 = Im\mathcal{X} - \int \frac{d\epsilon}{\pi} [\Gamma_2^L f_L(\epsilon) + \Gamma_2^R f_R(\epsilon)] ImG_2^r(\epsilon),$$

and

$$\mathcal{X}(\omega) = 2\lambda^2(N_2 - N_1) \left\{ \frac{1 - N_1}{\omega_r - \omega + i\Gamma/2} + \frac{N_1}{\omega_r + U_{12} - U_{11} - \omega + i\Gamma/2} \right\},$$

where  $\omega_r \equiv E_2 - E_1$  is the resonant frequency,  $\Gamma \equiv \Gamma_1 + \Gamma_2$ , and  $\lambda$  is the momentum matrix element for the inter-level optical transition.

Note that  $\mathcal{X}(\omega)$  consists of two poles corresponding to optical transitions from initial states at  $E_1$  and  $(E_1 + U_{11})$  to final states at  $E_2$  and  $(E_2 + U_{12})$ , respectively. The two transitions have different relative strengths which depend on the averaged steady-state occupation number in the ground state,  $N_1$ . The first term corresponds to the inter-level transition of a single electron in the QD [which occurs with a relative probability  $(1 - N_1)$ ], while the second term corresponds to the inter-level transition of a second electron in the QD (which occurs with a relative probability  $N_1$ ) under the influence of the first electron, which remains in the ground state at all times. In the latter case, the Coulomb repulsion between the two electrons give rise to an energy shift  $U_{12} - U_{11}$ . The fact that we have a fractional

occupancy  $N_1$  in a single quantum dot is attributed to the level mixing effect (coupling of the QD level to the continuum states in the leads) in the many-body open system.

The theory is applied to a realistic self-assembled quantum dot (SAQD) device. We consider an InAs/InGaAs SAQD system with conical shape. The SAQD is embedded in a slab of InGaAs with finite width,  $W$ . The slab is then placed in contact with heavily doped InGaAs to form an n-i-n structure for infrared detection. Within the effective-mass model[3], the QD electron is described by the equation

$$[-\nabla \frac{1}{2m^*(\rho, z)} \nabla + V(\rho, z) - eFz]\psi(\rho, \phi, z) = E\psi(\rho, \phi, z),$$

$m^*(\rho, z)$  is the position-dependent effective mass, which takes on values of  $m_G^* = 0.067m_e$  (for GaAs) and  $m_I^* = 0.024m_e$  (for InAs). The potential  $V(\rho, z)$  is equal to 0 in the InGaAs barrier region and  $V_0$  inside the InAs QD region. The potential in the depletion layers (which separate the slab from the leads) are modelled by an electrostatic potential  $V_d(z)$

$$V_d(z) = \begin{cases} \frac{-V_1}{D}(z + \frac{W}{2}) & \text{for } -(D + \frac{W}{2}) < z < -\frac{W}{2} \\ \frac{V_1}{D}(z - \frac{W}{2}) & \text{for } \frac{W}{2} < z < D + \frac{W}{2}. \end{cases}$$

For the purpose of constructing the approximate wave functions, we place the system in a large cylindrical confining box with length  $L$  and radius  $R$  ( $R$  must be much larger than the radius of the cone,  $r_c$ ). We adopt  $R = 400\text{\AA}$ ,  $D = 350\text{\AA}$ ,  $V_1 = -0.205\text{eV}$ , and  $W = 300\text{\AA}$  for all calculations. We solve the eigen-functions of the effective-mass Hamiltonian via the Ritz variational method. The wave functions are expanded in a set of basis functions which are chosen to be products of Bessel functions and sine waves

$$\psi_{nlm}(\rho, \phi, z) = J_l(\alpha_n \rho) e^{il\phi} \sin[k_m(z + \frac{L}{2})],$$

where  $k_m = m\pi/L$ ,  $m=1,2,3\dots$ . Throughout the paper, the origin of  $z$  is set at the middle of the confining box.  $J_l$  is the Bessel function of order  $l$  ( $l = 0, 1, 2, \dots$ , etc.) and  $\alpha_n R$  is the  $n$ -th zero of  $J_l(x)$ . 40 sine functions multiplied by 15 Bessel functions for each angular function ( $l = 0$  or  $1$ ) are used to diagonalize the Hamiltonian.

Fig. 1 shows the energy levels of the confined states with  $l = 0$  (solid line) and 1 (dotted line) as functions of height  $h$  of the QD with base radius fixed at  $R_0 = 70 \text{ \AA}$ . The other material parameters used here are: wetting layer thickness  $d = 3 \text{ \AA}$ , the conduction-band offset  $V_0 = -0.4 \text{ eV}$  (this includes the effect of hydrostatic strain due to the lattice mismatch between InAs and  $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}$ ), and length of the confining box  $L = 600 \text{ \AA}$ . At least two bound states for each angular function ( $l = 0$ , or 1) are found. For infra-red detector application, we are seeking an intra-band transition (between the ground and first excited state) at an energy around  $0.125 \text{ eV}$ , which occurs at  $h = 50 \text{ \AA}$ , for  $R_0 = 70 \text{ \AA}$ . The tunneling rates can be calculated numerically via the stabilization method as described in Ref. 3.

We only consider the zero temperature and low bias case, where the chemical potential at the left leads ( $\mu_L$ ) is lower than  $E_2$ , so that the average population in the excited state is small. Fig. 2 shows the photocurrent as a function of frequency for various applied voltages: solid line ( $V_a = 0.11\text{V}$ ), dotted line ( $V_a = 0.12\text{V}$ ), and dashed line ( $V_a = 0.13\text{V}$ ). The parameters used to obtain Fig. 2 are  $E_1 = -139\text{meV}$ ,  $E_2 = -14\text{meV}$ ,  $U_{11} = 10.4\text{meV}$ , and  $U_{21} = 7.2\text{meV}$ , which are all calculated based on the effective-mass model. The Fermi level in the source and drain region is assumed to  $E_F = 15\text{meV}$ . The broadening of the energy level  $E_1$  including all tunneling processes (dominated by the acoustic-phonon assisted tunneling in this case) is assumed to be  $\Gamma_1 = 0.01\text{meV}$ . The precise value of  $\Gamma_1$  is not important, since photocurrent is not sensitive to  $\Gamma_1$ . For the excited state, the broadening parameter is given by  $\Gamma_2 = \Gamma'_2 + \Gamma_2^R$ .  $\Gamma'_2$  is mainly due to radiative and non-radiative recombination from interacting with phonons and defects. The actual value depends on the sample quality and temperature. Here, we assume  $\Gamma'_2 = 1\text{meV}$ . The other contribution due to the direct tunneling is calculated via the stabilization method as described in Ref. [3]. The values are found to be  $\Gamma_2^R = 0.439\text{meV}$ ,  $0.545\text{meV}$ , and  $0.651\text{meV}$  for  $V_a = 0.11, 0.12$ , and  $0.13\text{V}$ , respectively. The spectrum of photocurrent consists of two peaks centered at frequencies  $\omega = E_2 - E_1$ , and  $\omega = E_2 - E_1 + U_{12} - U_{11}$ . The relative strength of these peaks are determined by the average occupation number in the ground state ( $N_1$ ), which is bias-dependent. As

shown in the figure, the Coulomb interaction leads to a double-peak photocurrent spectrum with energy separation related to the intra-level and inter-level Coulomb energies ( $U_{11}$  and  $U_{12}$ ).

For the QDIP characteristics, the photocurrent versus applied bias ( $J - V$  curve) is also of interest[7-9]. Fig. 3 shows the photocurrent as a function of bias for frequencies at  $\omega_r$  (dotted line) and  $\omega_r + U_{12} - U_{11}$  (solid line). Using Eq. (2) for the polarization, we can readily understand the behavior of photocurrent. The behavior of the photocurrent is determined by the prefactors  $(1 - N_1)N_1$  and  $N_1N_1$  for the two poles at  $\omega = \omega_r$  and  $\omega = \omega_r + U_{12} - U_{11}$ , respectively. At very low bias,  $N_1$  is small; thus, the magnitude of the solid line is much weaker than that of the dotted line. As the applied bias increases, the solid line displays a plateau due to the effect of Coulomb blockade on  $N_1$ . When the applied bias overcomes the charging effect,  $N_1 \approx 0.5$  and the solid line becomes almost identical to the dotted line.

In this study, we have used tunneling carriers as the source for photocurrent, in contrast to the captured carriers typically used in QWIPs. Due to the phonon bottleneck effect[4], it is predicted that the capture rate of the electron by the QD will be low. This could reduce the performance of QDIPs which use captured carriers as a photocurrent source. Using tunneling carriers as the photocurrent source will not have this drawback, and in this case we find that the effect of electron correlation leads to a double-peak spectrum and the photocurrent is a highly nonlinear function of the carrier density in the ground state  $N_1$ . Both of these effects must be taken into account in the analysis of photoresponse of QDIPs.

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### Figure Captions

Fig. 1. Energies of the bound states of a conical InAs/ $In_{0.2}Ga_{0.8}As$  QD as functions of height  $h$  of the QD with base radius fixed at  $R_0 = 70$  Å. Solid lines: ( $l = 0$ ). Dotted lines: ( $l = 1$ ).

Fig. 2. Photocurrent as a function of frequency for different applied voltages:  $V_a = 0.11V$  (solid line),  $V_a = 0.12V$  (dotted line) and  $V_a = 0.13V$  (dashed line).

Fig. 3. Photocurrent as a function of bias for incident frequencies at  $\omega = E_2 - E_1$  (dotted line) and  $\omega = E_2 - E_1 + U_{12} - U_{11}$  (solid line).







